Observations of a "weekend effect" in diurnal temperature range

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Using surface measurements of maximum and minimum temperatures from the Global Daily Climatological Network data set, we find evidence of a weekly cycle in diurnal temperature range (DTR) for many stations in the United States, Mexico, Japan, and China. The "weekend effect," which we define as the average DTR for Saturday through Monday minus the average DTR for Wednesday through Friday, can be as large as 0.5 K, similar to the magnitude of observed long-term trends in DTR. This weekend effect has a distinct large-scale pattern that has changed only slightly over time, but its sign is not the same in all locations. The station procedures and the statistical robustness of both the individual station data and the patterns of DTR differences are thoroughly examined. We conclude that the weekend effect is a real short time scale and large spatial scale geophysical phenomenon, which is necessarily human in origin. We thus provide strong evidence of an anthropogenic link to DTR, an important climate indicator. Several possible anthropogenic mechanisms are discussed; we speculate that aerosol-cloud interactions are the most likely cause of this weekend effect, but we do not rule out others.

The global mean surface air temperature has risen by ≈0.6 ± 0.2 K in the industrial era, and observations and model calculations suggest that human activities have played a significant role in this change in the Earth's climate (1). In addition to the global mean temperature, other observations are central to attempts to understand the nature and cause(s) of climate change, and thus to elucidate any links to human activities. One key indicator is the difference between the daytime maximum and nighttime minimum temperatures, referred to as the diurnal temperature range (DTR). Observations have shown that DTR has narrowed in many locations worldwide by up to 0.5 K per decade because nightly minimum temperatures have increased more than daytime values (2). Here we demonstrate a surprising aspect to this change: we show that the DTR reported from instruments in many regions is subject to a pronounced weekly cycle (hereafter referred to as a "weekend effect").

Natural mechanisms can contribute to changes in many climate indices, complicating the attribution of long-term climate change to an anthropogenic cause (1). In contrast, as no geophysical quantity that is independent of human activities can maintain a phase-lock with the weekly cycle over long time scales, observation of a weekly cycle directly links to human practices. The weekend effect in DTR has the important strength of being a short-period relative measure, and hence insensitive to such issues as changes in instrument placement or slow changes in the environment such as urbanization or land use. However, the possibility that an apparent weekend effect could reflect poor or inconsistent measurement practices by operators from day to day will be considered, and we will show that this is highly unlikely to explain the observations.

A few studies, some of them controversial, have reported weekend effects in local meteorological parameters and even in urban temperatures (3–6). On the other hand, weekend effects caused by vehicular traffic practices are well documented in studies of urban pollution and atmospheric chemistry (3–11). In this article, we first focus on observations that demonstrate the magnitude, spatial extent, and statistical robustness of the weekend effect in DTR. Although the thrust of this article is on the observation of this key climate indicator rather than on theories for its origins, we also indicate some possible sources of the effect, particularly short-lived atmospheric pollutants (e.g., aerosols) that can influence clouds and thereby DTR.

Data and Methodology

We examine data from the ≈10,000 worldwide surface stations with 40+ years of data as reported in the Global Daily Climatological Network (GDCN) data set. We concentrated our analysis on the 5,000 available stations in the continental United States. These surface data (obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center's Climate Analysis Branch) have been quality-checked but include observations at a broad variety of sites taken by many different observers. To ensure the highest possible data quality, we also isolated 660 "first-order stations" for some tests. First-order stations are where measurements are taken by certified observers at sites with a full range of meteorological instrumentation over a midnight-midnight time period; sites are operated by the National Weather Service, U.S. Air Force (Air Weather Service), U.S. Navy (Naval Meteorology and Oceanography Command), and the Federal Aviation Administration. These stations are likely to maintain consistent practices every day of the week. Using this reduced data set minimized the possible effects of operator biases, which could lead to an artificial weekly cycle. For many of these stations, including the case studies presented in Fig. 1, the descriptive information that is a required part of the meteorological measurement series was also carefully checked for any possible instrumental issues. As shown in Figs. 1 and 2, a further important feature is the consistency of observations not just at one but also at several nearby sites in a given region.

For our analysis of station data we included only those days when both maximum and minimum temperatures were recorded. We also included only those weeks that had no missing days. An annually averaged DTR was calculated for each weekday, using only these complete weeks of data. We further stipulated that at least 25 such weeks were needed for a representative annual average. These quality checks were essential. Note that ≈3% of U.S. stations occasionally had measurements only during the working week and these were excluded by our criteria. However, many other stations passed these checks with ease and nearly always had a full 52 weeks of coverage for all years in their records. The very large amount of daily data in a station's history is a strength of the statistical analysis presented here, because a complete 50-year time series of temperature contains 2,600 virtually independent data points for each day of the week.

GEOPHYSICS

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Abbreviations: DTR, diurnal temperature range; GDCN, Global Daily Climatological Network.

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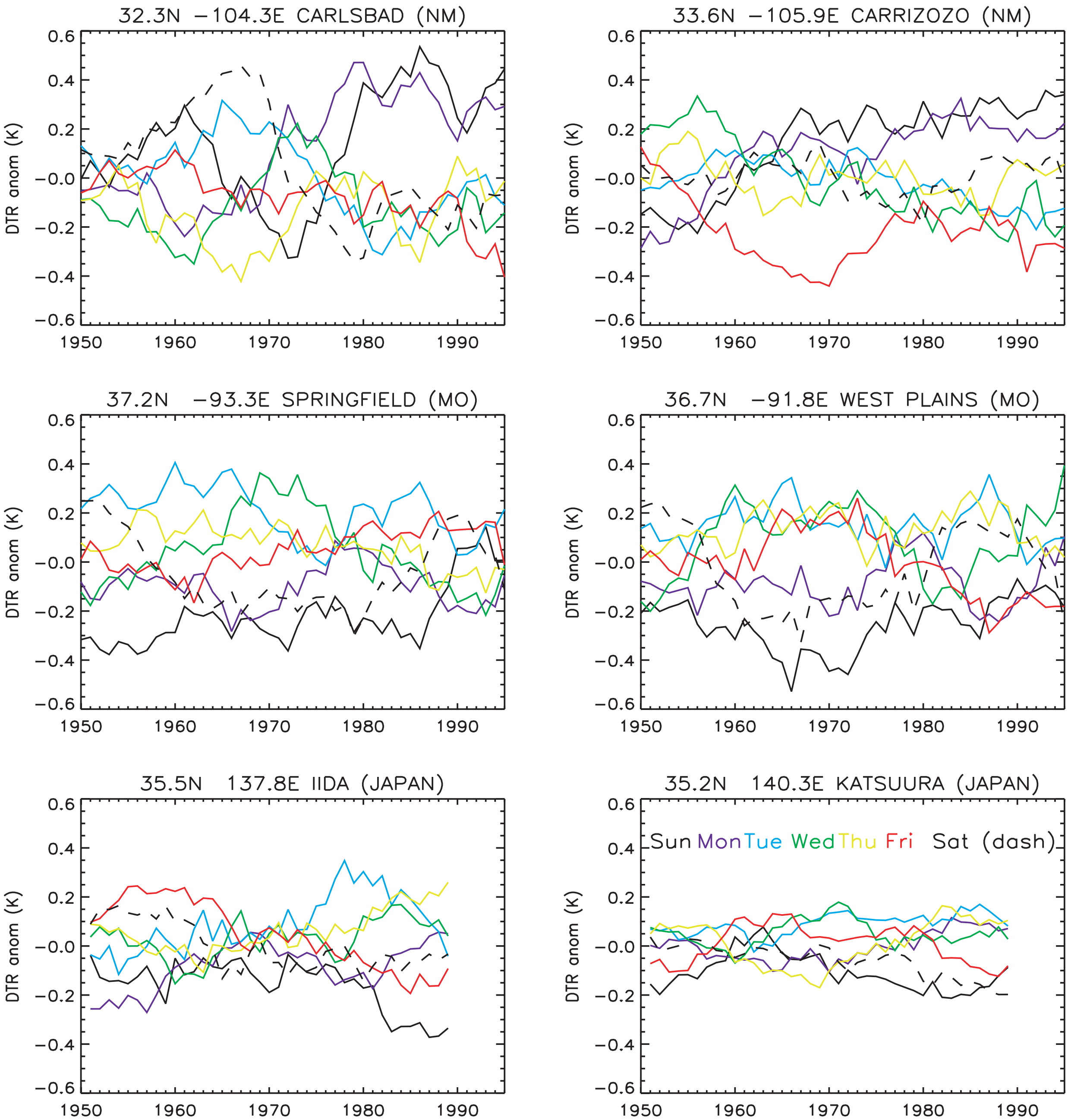

Fig. 1. Case studies for six stations. The annually averaged DTR (K) anomaly for each weekday, relative to the annually averaged DTR. A 10-year running mean has also been applied to the time series. The color code (see *Bottom Right*) refers to different weekdays.

For a given station each annually averaged difference between three weekdays' DTR and that of the weekend (see below) was computed, and the interannual variability of this difference was used to calculate the standard error in the mean. In the following figures and discussion, statistical significance is indicated only when it exceeds the 95% confidence level at a given station based on this temporal criterion. This methodology overestimates the error in the weekend effect, as it assumes that all of the interannual variability in weekday-weekend differences is a result of natural variability. When multidecadal averages are taken it is likely that socioeconomic changes play a role in altering these mean differences over time (e.g., as weekend driving practices may evolve; see below).

Case Studies

We begin with six case studies of first-order stations that illustrate different manifestations of the DTR weekly cycle, including its long-term changes over several decades. The stations chosen were typical of their regions as shown in Figs. 2 and 3. Here we illustrate the consistency of the observed weekend effect by showing pairs of nearby stations to demonstrate the spatial coherence. Fig. 1 shows the anomaly in daily and annual DTR relative to weekly mean values for three regions: New Mexico, Missouri, and Japan. The anomalies in each region exhibit both long-term trends and some interannual variability. Roughly 10 years of data were typically needed for the weekend signal to become statistically significant at the 95% level.

Many stations with a significant weekend effect exhibited at least some of the characteristics of the New Mexico time series

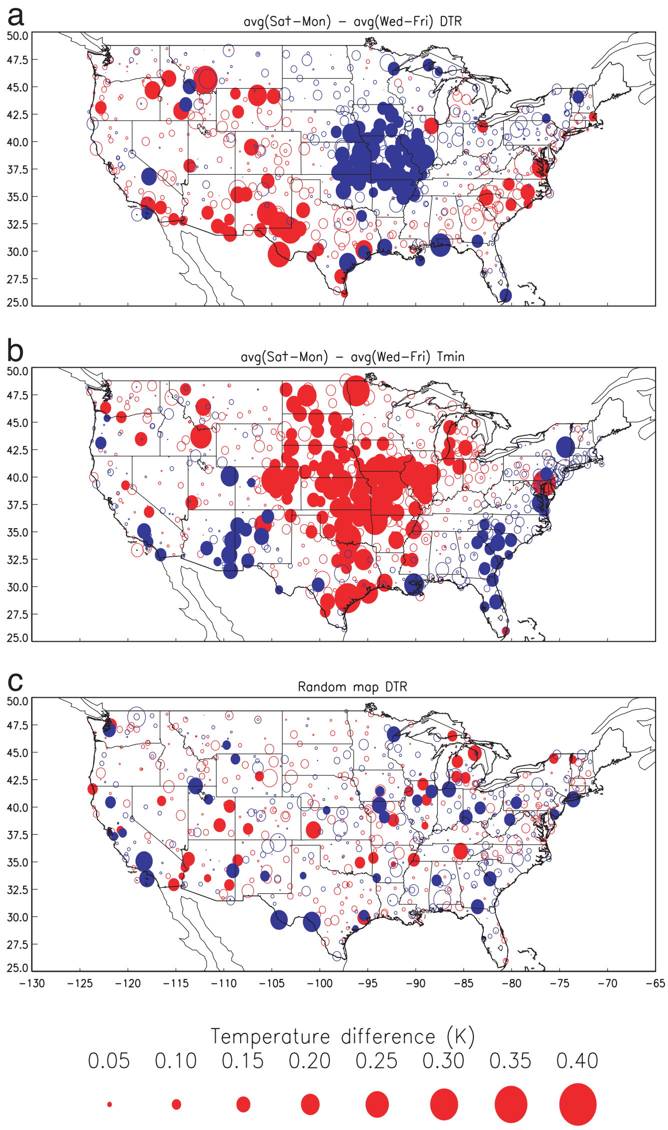

Fig. 2. Continental U.S. weekend effect for first-order stations, using complete station records. (*a*) The DTR difference (K) between the Saturday–Monday average DTR and the Wednesday–Friday average DTR (the DTR weekend effect). (*b*) The T_{min} difference (K) between the Saturday–Monday average T_{min} and the Wednesday–Friday average T_{min} (the T_{min} weekend effect). (*c*) The DTR weekend effect (K) from a typical numerical test case where the days of the weeks have been deliberately randomized; see text. Filled circles are temporally significant at the 95% confidence level. The diameter of the circle is related to the size of the DTR weekend effect in Kelvin.

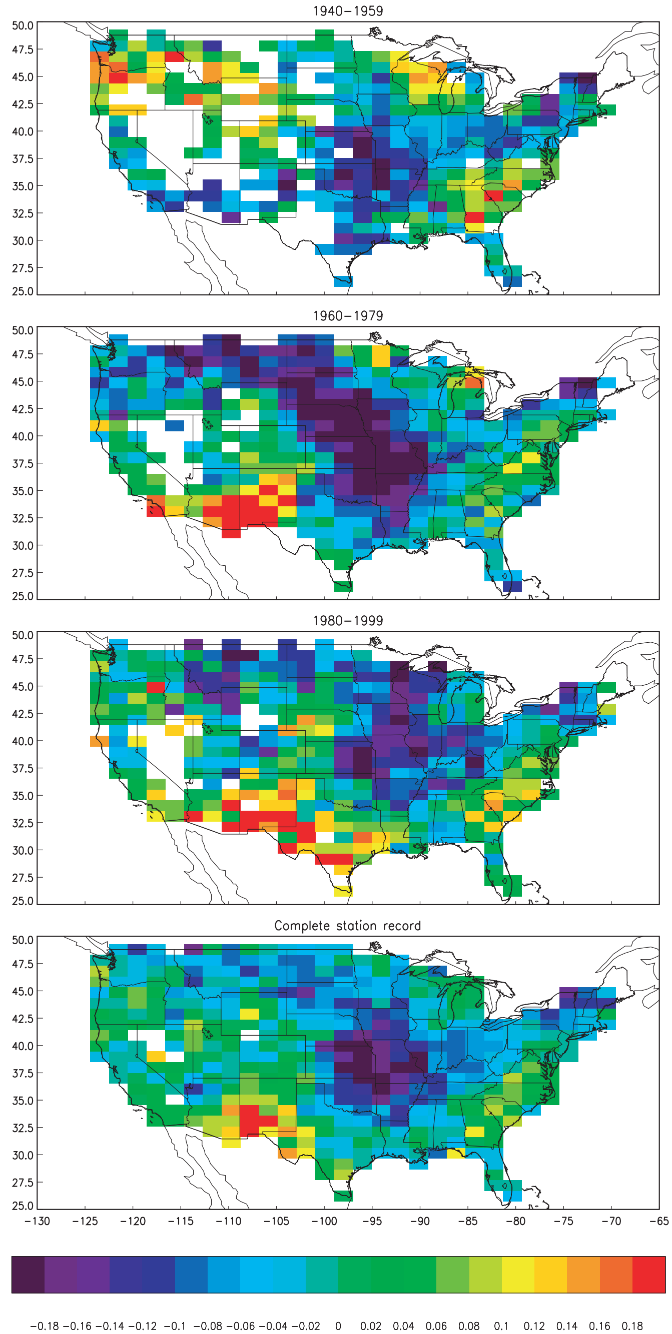

Fig. 3. Twenty-year averages of the mainland U.S. DTR weekend effect (K), using the entire GDCN data set. Three 20-year periods and the complete station record are shown. The weekend effect of each station has been averaged over 2° × 1° boxes, where each filled box has more than five stations with at least 10 years of data.

(Fig. 1 *Top*). These are: (*i*) Sunday and Monday had a consistently higher DTR than the other days since 1975; (*ii*) Friday was among the days of the week with the lowest DTR; and (*iii*) Monday often had a higher DTR than Saturday and was comparable to the DTR on Sunday, probably because the nighttime minimum recorded for Monday occurs during the night beginning Sunday. Although the detailed time variation of the weekly cycle at these two nearby locations are not identical, many similarities exist, and the correlations between the same day's anomaly time series at these two New Mexico locations are >0.5.

Not all stations had the same phase for their weekly cycle in DTR. We found that weekends could have a smaller DTR than the midweek days, especially in the American Midwest. Examples are shown for Springfield (MO) and West Plains (MO). Typical of this region, Tuesdays and Wednesdays generally displayed the largest DTR and weekends the lowest. Again, the time series of the days at the two nearby stations are correlated (≈0.6).

Although U.S. stations revealed some of the largest weekly cycles in DTR, many stations in other countries also exhibited a weekly cycle. As an example, two Japanese stations are shown (Fig. 1 *Bottom*), which both have their smallest DTR on Sunday. The magnitude of the weekly cycle in Japan is smaller than at many U.S. stations. However, all stations in Japan have the same sign for the weekend effect with good correlation between time series at many stations. We chose to define the weekend effect as the DTR difference between the average DTR on Saturday, Sunday, and Monday with the average DTR on Wednesday, Thursday, and Friday. We averaged over 3-day periods rather than 2 for more robust statistics and included Monday in our weekend based on the behavior indicated in Fig. 1.

These and other stations reveal weekend effects in DTR of the order of a few tenths of a degree, which can be compared with reported long-term global trends in DTR of ≈0.5° over the 20th century. This finding makes clear that understanding the weekend effect, whether it is an artifact of poor measurement practices or a physical effect, is critical to attempts to use DTR as a climate change indicator. In the following, we show further evidence that the weekend effect is a genuine climatic feature.

First-Order U.S. Stations

Fig. 2 presents results for all 660 first-order U.S. stations. It is noteworthy that some stations did not reveal any statistically significant weekend effect in records typically 50 years in length. However, >35% of the stations were found to have a significant weekend effect of the order of several tenths of a degree (Fig. 2*a*). A distinct spatial pattern in DTR changes was found over the U.S., where DTR was higher at weekends over a number of stations in the Southwest and the Piedmont region of the Southeastern U.S. in North and South Carolina and Georgia. The Midwest displayed the opposite signal, with smaller DTR at the weekends. T_{max} differences were barely significant. T_{min} differences (Fig. 2*b*) revealed a regional pattern of change that was similar to that of DTR, with higher T_{min} values during weekends in the Midwest and lower T_{min} in the Southwest and Piedmont. Our method of illustration highlights the large weekend effect at the 35% of stations with robust statistics. As in Fig. 1, the great majority of these stations were not urban. Nearby stations generally had the same sign for their weekend effect, although in many cases it was smaller than those found at the significant locations and not statistically significant. This geographical similarity of the weekend effect suggests that it is unlikely to be caused by operating practices but may be linked to local effects.

Pattern Significance

It is possible that variability of a random phase, combined with spatial coherence of surface temperature changes, could generate such patterns as seen in Fig. 2 *a* and *b* by chance. Synoptic scale disturbances have time scales of the order of 10 days and could display apparent weekend effects over short time periods. Although such effects would be unlikely to persist over time scales of several decades as shown here, a quantitative test is needed to rule out such effects. We tested the significance of these patterns by applying a field significance test (12). A series of 1,000 random maps were generated by using the same data by arbitrarily ascribing January 1 in each year to a random day of the week rather than the true day. We then looked for a weekly cycle in this randomized data. A typical randomized data map is shown in Fig. 2*c*. Usually a field is deemed significant if 95% of the random maps generated have a lesser number of significant points than the true map. For our DTR differences, the real weekend effect (Fig. 2*a*) had 250 temporally significant points, and the random maps had an average of 110 ± 30 (1σ) temporally significant points (Fig. 2*c*); this finding implies the pattern of DTR differences (Fig. 1*a*) are significant at an extremely high level (>99.9%). The T_{min} pattern (Fig. 2*b*) was found to be significant at the 95% level, and the T_{max} pattern (data not shown) was barely significant at only 70%. The similarity of the DTR weekend effect pattern between different 20-year subsets of the data as shown in Fig. 3 also illustrate that a random cause of the DTR pattern is extremely unlikely.

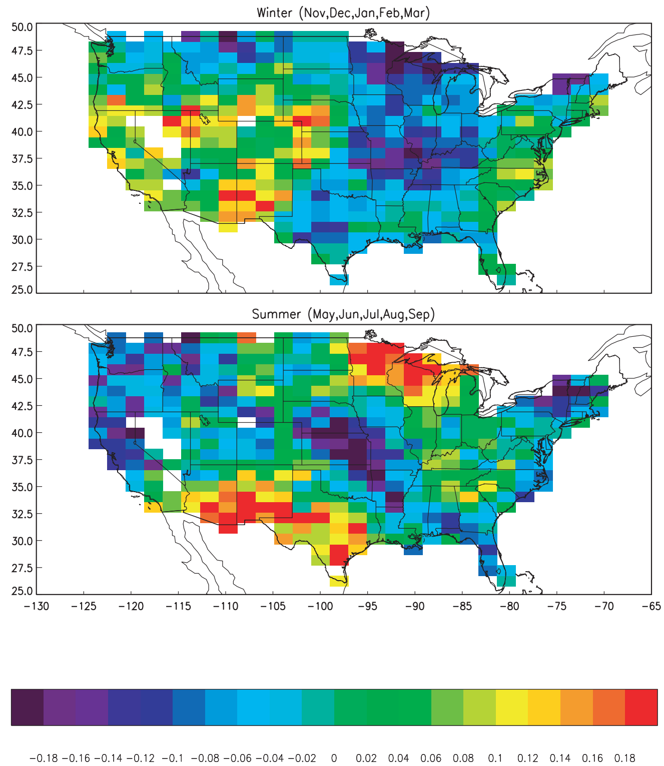

Fig. 4. Seasonal mainland U.S. DTR weekend effect (K). The weekend effect for winter (*Upper*) and summer (*Lower*) months, using complete station records and the entire GDCN U.S. data set.

Data from the entire GDCN U.S. network of 5,000 stations revealed a very similar weekly cycle to those in the first-order subset. In this data set, the DTR pattern significance was even higher, and again >35% of stations had a temporally significant weekend effect over the length of their records. To give a more robust statistical evaluation our subsequent results are based on the whole data set.

Long-Term Changes in U.S. Weekend Effect

Fig. 3 presents the data from the entire GDCN network over the U.S. binned in 20-year intervals and averaged over the full records. As there are too many stations to show individual station data, we binned stations into 2° × 1° regions and found the average weekend effect in each grid box containing five or more stations.

Each of these three 20-year periods since 1940 had a significant weekly cycle based on the same randomized test shown above for the first-order stations (pattern significance >99.9%). We can therefore virtually rule out random variability. Although the overall pattern of the U.S. weekend effect in DTR is evident in each 20-year period since 1940, there have been some significant changes in some regions. There appears to be a lessening of the weekend effect in the Great Lake states (but see Fig. 4 for the seasonal cycle in this region). The Midwest negative weekend effect appears largest during the 1960–1979 period, and the Southwestern weekend effect appears to be strongest in the last 20 years. These observations not only strengthen the case for the weekend effect but also suggest that the long-term trends in DTR over the past century in certain regions are linked in part to the processes causing the DTR weekend effect.

Seasonal Variations

The winter and summer U.S. weekend effects are shown in Fig. 4. For New Mexico, Arizona, the Midwest, and some Eastern

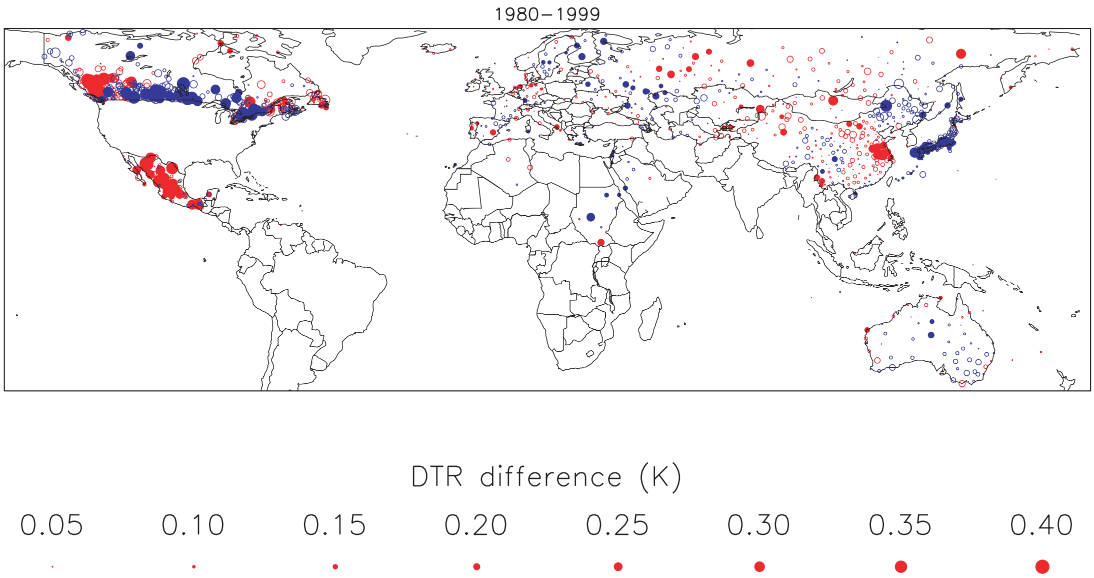

Fig. 5. Weekend effect for stations outside the U.S., using 1980–1999 data. Filled circles are temporally significant at the 95% confidence level. The diameter of the circle is related to the size of the DTR weekend effect in Kelvin.

states the weekend effect generally occurs during both seasons, with several places exhibiting a larger summer-season weekend effect, which can be as much as 0.2 K. The Great Lakes region and western states exhibit large seasonal differences in their weekend effect. The Great Lakes states, in particular, have a large positive weekend effect during the summer and a negative effect during winter months. The generally stronger weekend effect in the summer season is qualitatively consistent with the previously observed larger DTR trends in the summer (13).

Other Meteorological Parameters: Clouds and Precipitation

Observations have suggested that cloud changes are linked to the long-term trends in DTR, and correlations between DTR and cloud cover, over certain regions, have been found to be as high as 0.9 (14). Therefore, it is worthwhile looking for evidence of a weekly modulation in cloud or cloud proxy data. We examined both precipitation data from the same stations and observations from the 1983–2000 International Satellite Cloud Climatology Project (ISCCP) (15) records for weekly cycles. These observations did not display strong evidence for weekend effects. However, it should be noted that the variability and the measurement uncertainties in cloud and precipitation data are larger than those of observations of DTR. The satellite data did not reveal a significant weekend effect in cloud fractions or optical depths, but the weekly cycle would have had cloud fraction changes of >5% to be detectable against the variability in the data. We also analyzed the precipitation data from the GDCN stations in a similar fashion to the temperature data. As found for the ISCCP data, the 20-year patterns are barely significant at ≈70% and the longer-term pattern was ≈80% significant. The only statistically robust feature of the precipitation pattern indicated more rainfall in the Midwest at the weekends, which could support the hypothesis of more cloud and a depressed DTR at the weekend. However, a clear weekend signal for precipitation or cloudiness over long periods could not be distinguished from the variability in these data sets.

The Rest of the World

A total of 2,178 stations with 40+ years of data were analyzed for a weekend effect from the rest of the world. Generally the last 20 years (Fig. 5) had the largest weekend effect, especially in Japan and China. Outside of North America the magnitude of the weekend effect is notably smaller (see also Fig. 1). Taken as a whole the pattern in Fig. 5 is not significant. However, the China-Japan region and Mexico are significant (>95% pattern significance) if taken in isolation. Interestingly and perhaps surprisingly, Europe shows no significant pattern of weekend effect. Although many individual stations in Canada appear to show a large temporally significant effect, the overall pattern is not statistically significant at the 95% confidence level.

Discussion

It has been suggested that lunar effects project onto the weekly cycle (16); however, our data did not reveal a significant 28-day cycle, so this hypothesis can be rejected. To our knowledge there is no other known naturally occurring method of generating a weekly cycle; therefore the weekly cycle we have observed in DTR could either arise only from an anthropogenic cause or random (e.g., synoptic scale) variations that project onto the weekly cycle by chance. With rigorous use of pattern testing statistics throughout this work (Fig. 2) and through the observation of similar weekend effects over longer and shorter records (e.g., Figs. 3 and 4) we can eliminate a random cause. A nongeophysical anthropogenic cause could arise from weekend differences in recording practices at individual stations. Although this is likely to be the case for a few isolated stations, the large-scale nature of the weekend effect patterns, the presence of the same weekend effect in first-order stations, and careful checking of station metadata makes this explanation extremely unlikely. We are therefore left with real anthropogenic cause(s) to try and identify. A full identification of the physical processes involved is outside the scope of this article, but we briefly discuss the relevance of our observations and available literature to possible causes.

First, any effect found needs to alter the DTR on a time scale of hours-days. Therefore, several possible causes that act only over long time scales, such as well-mixed greenhouse gas changes, can be ruled out. Practices that rapidly alter ground moisture or surface albedo could cause a weekly cycle in DTR. For example, flooding or plowing a field are potential causes, whereas planting a crop, which subsequently grows and alters the surface albedo, would not contribute to a weekend effect, nor would urbanization. Although a weekly cycle in agricultural practices cannot be ruled out, these would be expected to have a very strong seasonal bias. Over much of the Midwest such a seasonal variation is not seen. However, it remains a possibility elsewhere. Urban heat island effects have also been proposed as a possible cause of a weekly cycle in temperature over Melbourne, Australia (5). However, we also examined the weekend effect by using stations from the Historical Climatology Network (17), where urban stations had been explicitly removed; we found no noticeable difference in the weekend effect between the two data sets.

Relatively short-lived gases or anthropogenic aerosol emissions are potential causes, either directly or indirectly through their interaction with clouds. Several modeling studies have implicated aerosol and aerosol cloud interaction as possible causes of long-term DTR trends (18–20). Further, weekly cycles have indeed been observed in ozone and other surface pollutants in environments ranging from the polluted cities of California (21) to Switzerland (7) and the more remote regions of Canada (11). A study from Toronto also linked a weekly cycle in ozone to temperature (6). However, if low-level ozone change were to cause DTR changes it would need to affect $T_{\min}$ and $T_{\max}$ differently by having a significant effect on solar radiation. Because of its strong solar absorption in the stratosphere, low-level ozone absorbs only very small amounts of radiation (typically less than a few tenths Wm^{-2}) and the weekly modulation would be a fraction of this amount: this absorption would be unlikely to cause the observed magnitude of the DTR weekend effect. Direct anthropogenic aerosol changes primarily absorb or reflect solar radiation and would therefore be expected to impact $T_{\max}$ more than $T_{\min}$. As the weekend effect is predominately felt in $T_{\min}$ (Fig. 2), we believe cloud changes are the most probable cause of DTR differences. As aerosol indirect effects have been observed particularly over oceans and are known to operate on short time scales (1) we believe that the observed weekend effect is likely to be linked to aerosol-cloud interactions.

Any hypothesized cause(s) would, however, need to explain why the weekend effect varies with location. Depending on background meteorological conditions, opposite weekly cycles have been observed for ozone (7). However, as we believe ozone is unlikely to be the cause of the DTR weekly cycle, other reasons need to be explored. Here we suggest three possible reasons for the pattern. First, a different aerosol mechanism could be operating over different regions, because different types of aerosols can produce differing effects on clouds. For example, a semidirect aerosol forcing has been proposed whereby absorbing aerosol can reduce cloud cover in some environments (22). This mechanism could be operating over the Midwest and Japan to reduce cloud cover and elevate the DTR during the working week. In contrast, at locations where a positive weekend effect is seen, indirect aerosol effects could be creating thicker and/or longer lasting cloud during the working week, which leads to a smaller DTR. Second, it has been proposed that aerosol heating can lead to large-scale circulation changes (23). A weekly cycle of aerosol effects on circulation could lead to spatially varying patterns in DTR differences. Third, there could be a gradual phase shift in the weekly cycle across the U.S. from the transport of pollutants downwind. For example, Midwest stations have their maximum DTR usually on Tuesday or Wednesday (see Fig. 1), ≈1–2 days downwind of potential West Coast sources of pollution. Some studies have reported long-range transport of weekend effects in measured surface air pollutants over very broad areas far removed from urban sources (11). Fuller examination of possible mechanisms is beyond the scope of the present article. Although the data support a link to human activities, it should be noted that a link to pollution processes other than those relating to clouds and aerosols are not ruled out by this study.

Conclusions

We have found significant weekly cycles in DTR in many regions that have a comparable magnitude to long-term trends in DTR over the past century, providing evidence for a short time scale human influence on this critical climate change indicator. The observations provide important information for studies that attempt to identify fingerprints of climate change processes. The identification not only of the presence but also of the absence of a weekend effect in DTR could provide useful information for climate studies. Such data can likely help to separate influences on climate caused by short time scale phenomena from those linked to the long-term well-mixed greenhouse gas changes. For example, regions with no weekend effect may prove a good location to isolate a long-lived greenhouse gas signal. On the other hand, those regions displaying large weekend effects suggest that other pollutants such as aerosols may play a larger role in DTR over broad areas than previously recognized. If indeed these phenomena are linked to aerosol/cloud interactions, then further study of the weekend effect could provide insight into those important processes. The data strongly support the view that human emissions play an important role in climate change and represent a key test for climate change theory.

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